Journal of Cleaner Production 172 (2018) 4018–4032

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

System dynamics model of a biotechonomy

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ARTICLE INFO

Article history:
Received 8 July 2016
Received in revised form
2 February 2017
Accepted 19 March 2017
Available online 20 March 2017

Keywords:
System dynamics
Biotechonomy
Bio-economy
Renewable sources
Bio-resources
Sustainability
Climate change

ABSTRACT

The need for substitution of fossil resources with renewable alternatives, for an efficient use of the bio-resources, and for the development of knowledge-intensive sustainable economies call for the design of policies to create and govern biotechonomic systems. The goal of this study is to create a tool to facilitate such policy design, - aimed at the development of biotechonomic systems by use of a system dynamics model. This model constitutes a general framework for the representation of critical biotechonomic sectors; their land use, production and consumption of raw material, research and development, investments in and utilization of production capacities (i.e. capital investments), their utilization of labour, finances (value creation, capital and operating costs and profit), and sustainability. A sustainability index, based on emergy is applied to assess the environmental performance of the various sectors considered. Moreover, the model is operational and lends itself to the simulation of the development of these sectors, both past and future. This model may be applied to a variety of biotechonomic sectors and extends to the cyclical economy at large. As the purpose of this model is to facilitate the development and testing of policies, the model allows for the inclusion of structural components that represent such policies, including the extension of production lines, the utilization of taxes and subsidies to modify the land use and to encourage the redirection of materials, and support for the investment in research, development and capital. Model is applied to example of birch use as raw material. Results show that model framework can be applied to micro, meso and macro level planning and policy making.

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1. Introduction

The bioeconomy concept is becoming more prominent topic in science and policy lately. In 2012 European Commission within a strategy "Innovating for Sustainable Growth: A Bioeconomy for Europe" defined bioeconomy concept (COM, 2012). The strategy defines that bioeconomy is based, first of all, on using renewable biomass, by using not only raw material, but also biomass residues and, second of all, producing wide range of high added value products and energy. Production of high added value products means that at first biomass is used to produce high added value products like pharmaceuticals and chemicals and then residues are used for the production of lower added value products. Therefore, the main aim of bioeconomy is to use bioresource as fully as possible and reduce waste. Bioeconomy is based on three pillars – knowledge creation, research and development and innovation. This principle is called cascade combination of technologies. Moreover, bioeconomy is closely linked to circular economy. If conventional economy is based on the concept of *take*, *make* and *dispose* (Ness, 2008) then in contrast circular economy is based on the principle of reduction, reuse and recycling within product manufacturing, transportation, purchasing and consumption. Therefore, the aim of circular economy is to increase sustainability by reducing waste. However, it should be noted that economy cannot be completely circular, because there might be a point when recycling of a material is too expensive to be economically feasible. Bioeconomy faces number of dilemmas such as: (1) the competing goals dilemma, (2) the incumbent vs. new entrant competition dilemma, and (3) the industry boundaries dilemma (Boehlje and Bröring (2011)). These dilemmas are part of a list of challenges that arise from the very complex structure of the bioeconomy system.

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http://dx.doi.org/10.1016/j.jclepro.2017.03.132
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In the context of this study biotechonomy combines innovative technologies for bio-resource production and processing into higher value added products. The term indicates particular focus on the technologies for an efficient use of bio-resources although there is no principal distinction from the bio-economy concept.

Bio-resources, as substitutes of the fossil ones require efficient use, since although being renewable, can be depleted if over-utilized (Roger et al., 2011). In the review study by Scarlat et al. (2015) on the bioeconomy policy framework in European Union, it is indicated that with a growth of such sectors as biomaterial production and green chemistry, and increased demand from the bioenergy sector a competition for the biomass resources will intensify and the biomass sustainability is a critical issue.

A review carried out by Ghisellini et al. (2016) reveals that transition towards circular economy has been mostly a bottom up process that is initiated by various environmental organizations, society, as well as nongovernmental organizations. In some cases transition to circular economy is part of a national political strategy. They also conclude that success of implementation of circular economy is based on involvement of society as well as economic return of investment which serves as motivation for companies and investors. An interdisciplinary framework approach is crucial to speed up transition towards circular economy. Lancker et al. (2016) findings agree with Ghisellini et al. (2016) that variety of studies on bioeconomy exist. One part of studies are focused on the technological and innovation aspect (micro level), while other studies are shedding light on social, economic and environmental issues of implementing bioeconomy at meso and macro levels.

Studies on bioeconomy policy making reveal that although bioeconomy concept is very a complex multi-disciplinary approach it is important to involve stakeholders such as farmers, foresters, entrepreneurs, researchers, public officers, non-governmental organization representatives and bank officers in the decision making process. Moreover, this type of approach allows creating new cooperation networks among different stakeholders and sectors (e.g. Sisto et al. (2016), Mohan et al. (2016), Pfau et al. (2014)). Policy planning and decision making tools would be of great help for stakeholders to take into account all aspects and impacts of transition towards bioeconomy.

Few tools have been used to assess bioeconomy impact, for example, Cristobal et al. (2016) investigated three bioeconomy value chains (food and feed, bioenergy, biobased products) to assess their environmental performance using life cycle assessment. Musango et al. (2014) have applied system dynamics model of the Green Economy Model to South Africa case. The model is based on top-down approach and give insight into factors that influence green economy development.

Review of the existing research reveals a lack of studies on biotechonomy policy design based on models which represent a general framework, i.e. considering a cross-sectoral interrelation and complexities associated with that. The knowledge gap asks for studies which focus not only on efficient utilization of a biowaste but policy design for the optimal allocation of land and investment among alternatives of raw material supply for value added product production.

The research question of this study is the following: What is the structure of a generic framework model for a biotechonomic sectors; their land use, production and consumption of raw material, research and development, investments in and utilization of production capacities (i.e. capital investments), their utilization of labour, finances (value creation, capital and operating costs and profit), and sustainability. The model resulting from the research considers delays associated with re-allocation of land for alternative use and thus the availability of raw material, the establishment of production capacities for the processing raw materials into derivatives, and the acquisition of knowledge and skills (competence) enabling the effective and efficient utilization of current production lines as well as the extension of such lines into new profitable and sustainable forms of production. The considered systems are complex and structurally characterized by:

- accumulation processes, causing delays in their response to incentives;
- feedback processes, causing a reinforcement or dampening of such a response;
- nonlinearity, causing an interaction between the response produced by various sector components and across sectors;
- uncertainty.

In what follows, we present the generic model framework, its validation and application to the forestry sector focusing on birch-derived products of the techonomy, and a discussion focusing on the framework as a foundation for the assessment of policy instruments aimed at stimulating a profitable and sustainable development of the biotechonomy. In Section 2 the methodological framework is outlined. It is followed by Section 3 where the validation of developed methodological framework is described. Section 4 gives insights into application of developed methodological framework. Section 5 provides results. Finally, discussions and conclusions follow.

2. Methodology

System dynamics modeling is well-suited for the representation of such systems. This approach was developed by Jay Forrester (1961) and is referred to as the “white box” or causal-descriptive modelling tool. For the “white box” models, the validity of the internal structure of the model is essential, because the behaviour of the system can be modified by adjusting its structure (Barlas, 1996). PowerSim Studio has been used as software tool for building stock and flow structure and simulation of system’s behaviour.

The model presented in this study fills the gaps of the current approaches by adding opportunity to study feedbacks linking the added values by the production of derivatives, calculated per unit of land or raw material, via the allocation of land and the production of such raw materials, to the allocation of materials for various production chains. Below are some of the policy issues that may be addressed by way of such a model:

1) How should the land be allocated across alternative forms of raw materials production, considering the resulting total value added per unit land?
2) How should the raw material be allocated across alternative forms of production of derivatives, considering the resulting total value added per unit of raw material?
3) How should investments in research, development, capital and labour be made, considering resulting total value added per unit of investment?
4) How may taxes and subsidies contribute to redirect the land use, flows of material, investments in research, development, capital and labour in the direction of high value added production lines.
5) What are the effects of delays in the response to reallocation and the application of taxes and subsidies, the resulting interaction between various sectors, and the associated uncertainty?

2.1. Generic model framework

A generic model framework is one that may be applied to a number of different sectors of the biotechonomy and also across

such sectors. The sectors are interrelated by their utilization of land, consumption of raw material and its derivatives, allocation of financial resources and labour, and investments in research and development. Between them there is a competition for inputs where profitability and sustainability are drivers and where taxes and subsidies (and other public policy instruments such as legal measures) may be applied as incentives to redirect the development.

2.1.1. General structure of generic model framework

The generic model framework consists of 10 interrelated modules, portrayed in Fig. 1. In what follows we will discuss these modules in some detail.

2.1.1.1. Land and raw material production. Land (including lakes, streams and inlets) is the most fundamental resource in the bio-economy. Any production of bio-products is based on land in which the nutrients are located and the bio-products that constitute the raw material of the biotechonomy may be produced. The amount of land allocated for various kinds of production, depends on a number of factors. Typically, current land use is determined by the yield of production of various bio-products offered by that land and the price of that commodity. Yield is an expression of land productivity, i.e. how much of a certain commodity may be produced per hectare land. The larger the yield, the more may be produced per hectare and, with a certain product price, the larger are the revenues from such production. Whether land will be used for the production of a certain commodity, is determined by the profitability of such a production, whether the yield and price justifies the expenditures associated with such a raw material production, - compared to alternative forms of land use.

The expenditures depend on the market price of the additional factors of production (including financial expenditures associated with capital investments, the cost of fertilizers and the cost of labour). Considering land as a factor of production, its yield depends on the location and the constitution of the land; i.e. the nature of its soil, its nutrients and its micro-climate (temperature, precipitation etc.). Significant uncertainties may be associated with these factors, - such as the local weather conditions. In addition, the technological level of physical capital and the educational level of human capital are determinants of yield (i.e. productivity).

More specifically, the total available land is allocated among raw material production activities corresponding to the profit which can be generated per unit of land by use of logit function. Namely, if the perceived total annual profit per 1 ha of the land use area from raw materials 1, 2 and n is P_1, P_2 and P_n then the "indicated land use fraction" for the production of the raw material 1 is calculated as follows:

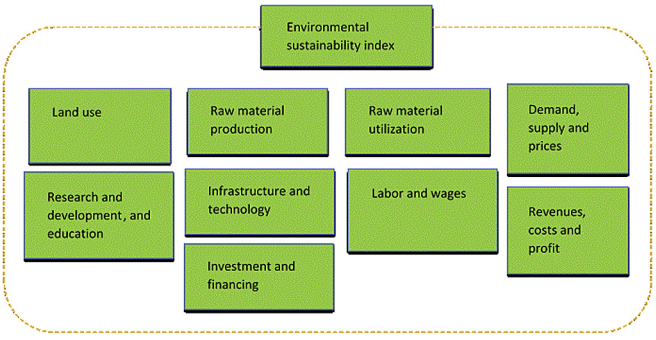

Fig. 1. Structure of the bio-economy model.

$$ILUF_1 = \frac{e^{\propto P_1}}{e^{\propto P_1} + e^{\propto P_2} + \ldots + e^{\propto P_n}}, \quad (1)$$

where $ILUF_1$ – indicated land use fraction for the production of raw material 1;

$P_{1\ldots n}$ – perceived total annual profit per unit land from production of a raw material, (thous. EUR/ha)/year;
α – parameter affecting a rate of transition between productions of alternative raw materials in response of change of the perceived total annual profit per unit of land (i.e., steepness of the curve).

If the perceived total annual profit per unit land is equal for all raw materials, i.e. $P_1 = P_2 = \ldots = P_n$ then according to the Equation (1) the indicated land use fractions are also equal, i.e. $ILUF_1 = ILUF_2 = \ldots = ILUF_n$. As the perceived total annual profit per unit land of the particular raw material value chain increases, then the fraction of the land allocated for production of this raw material increases on expense of the other raw materials. It takes time to re-allocate a land for another activity therefore the actual land use area for production of a raw material (e.g. the raw material No. 1) is calculated by using 3rd order material delay function with delay time of 10 years:

$$LUA_1 = DELAYMTR(ILUF_1 \cdot TAL, 10, 3), \quad (2)$$

where LUA_1 – land use area for production of the raw material No 1, ha;

TAL – total available land, ha.

2.1.1.2. Raw material utilization; the production of derivatives. The raw material from bio-production may be sold to the market as it is, with no (or minor) additional processing: Apples or firewood may be sold after harvesting with a minor processing investment (for packaging, chopping etc). In many cases, derivatives may be produced. For example, the raw material, such as apples and wood, produced from the land, may be refined in subsequent production to derivatives such as apple cider and plywood. Derivative production will add value to the products, - over and beyond the value of the raw material. On the other hand, it will fuel the demand side of the economy by requiring capital investments and labour, - i.e. carry costs. From a private sector perspective, such derivative production will take place if it is economically justified, i.e. it is profitable. From a public sector perspective, it will take place if it serves the national economy (including reduced unemployment) and is sustainable from an environmental point of view.

2.1.1.3. Capital investments; investment and financing in infrastructure and technology. The profitability and sustainability of a certain production, whether of raw material or derivatives, is indicative of the volume to be produced and thus the investments made in that production. To what extent a certain volume of production may materialize, depends of the current land use (and the raw material produced on that land) and the human and physical capital (characterized by the required level of technology and education) available for that production. In times of restructuring, there is, typically, a gap between the availability of raw material and capital available and what is required to meet a target production volume. And it will take time to close that gap, - to generate financial means, to reallocate land, to modify the capital levels and to hire and educate the workforce. It might take even longer to complete the

research and development required to utilize the raw material effectively and efficiently in derivative production.

More specifically, as illustrated in the stock-and-flow diagram in Fig. 2, the production capital is represented in the model by way of its resulting capacity and is driven by the availability of raw material, i.e. the inflow of raw material to the production (determined by the target production volume). In the model, "capacity" is represented in two forms;

- the capacity on order that accumulates the capacity (capital) order rate and is drained by the commissioning rate (corresponding to the capital instalment rate);
- the capacity in operation that accumulates the commissioning (instalment) rate and is drained by the decommissioning rate (corresponding to the capital discard rate).

The capacity order rate is acting to control the capacity on order and in operation. It consists of 3 components. The first one is the decommissioning rate, - it must compensate for decommissioning. Moreover, there is the adjustment of capacity in operation and then there is the adjustment of capacity under construction. Each of these adjustments forms a negative feedback loop that drives the value of the stock by way of the capacity order rate. The desired (target) stock values towards which the stocks are driven are determined as follows:

- The desired capacity in operation is determined by the availability (inflow) of the raw material.
- the desired capacity on order, on the other hand, is determined by the desired commissioning rate and the time is takes to deliver that capacity.

Moreover, the desired commissioning rate is determined by the decommissioning rate and the adjustment of the capacity in operation. The adjustments of the stocks depend on the gap between the desired and the actual stock values and the time it should take to close that gap.

2.1.1.4. Revenues, costs and profit. The revenues gained from selling the product in a market, is determined by the volume sold and the price obtained for the product in that market. The revenues must justify the costs associated with that production. These costs consist of the capital costs, resulting from the investments made, and the cost of operation, including labour and raw materials costs. A larger capital utilization reduces the capital cost per unit produced. Moreover, a larger production volume and a larger cumulative production (indicating a positive learning effect) may also contribute to a reduction of unit costs.

2.1.1.5. Demand, supply and prices. In this model, we assume that the products are being sold at a fixed price, determined by the price on the international market. This is true for raw material as well as for derivatives. I.e. it is assumed that the production is not sufficiently large to influence the market price.

2.1.1.6. Labour. The work force (labour) is acquired at the labour market. The cost of labour (salary level) reflects the level of education to be held by the work force. This is determined by the technology-level characterizing the physical capital employed. Moreover, as in the product market, we may introduce a demand and supply sector to determine the cost (price) of labour (salary level). In this model, the salary level is fixed and determined by the level of education required, i.e. by the technology level of the physical capital employed in production.

2.1.1.7. Research and development. Research and development

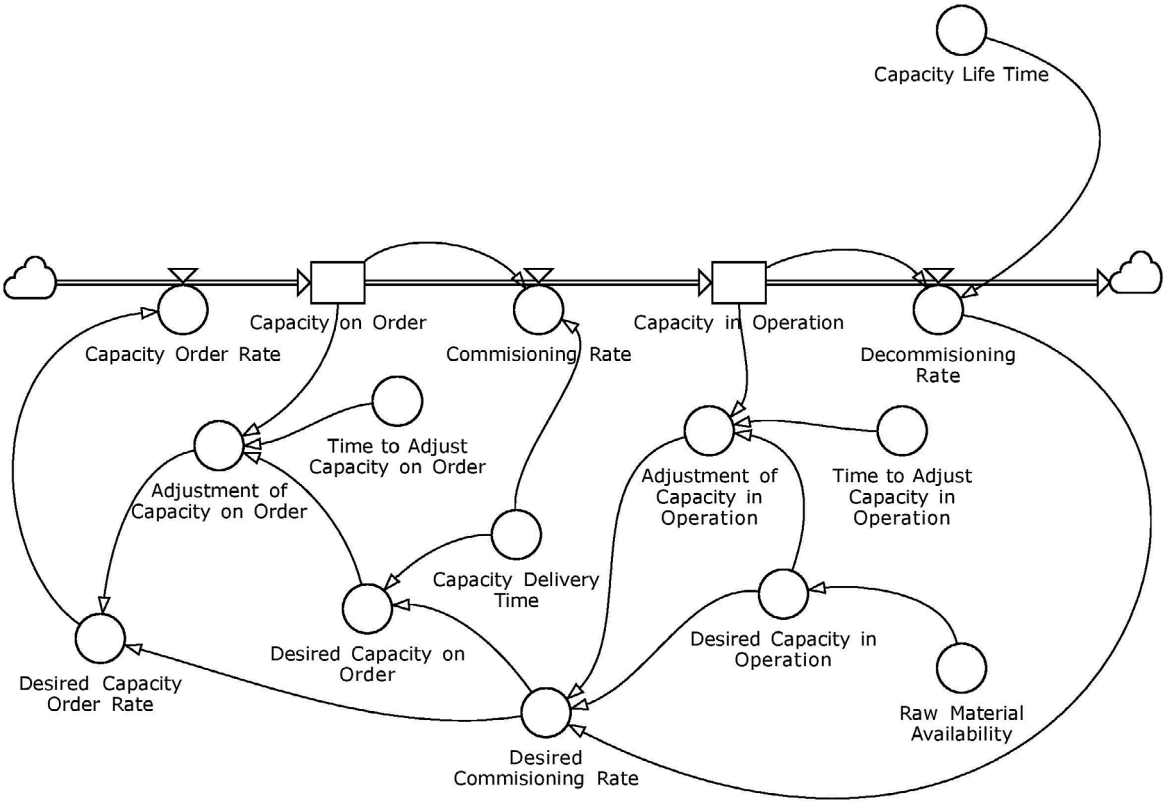

Fig. 2. A stock-and −flow diagram of the physical capital sector.

leads to the development of new products and production lines. Moreover, it may increase the effectiveness of production enabling product improvements (yielding a higher market value) and a larger production volume per unit raw material (better raw material utilization). Also, it may increase the capital efficiency through technology improvements, implying an increased yield per (physical and human) capital unit.

2.1.1.8. Environmental sustainability; environmental impact and tax. Environmental impact of products, whether raw material or derivatives are assessed by employing the environmental sustainability index, calculated based on the emergy expenditure associated with their production. Production may be considered non-sustainable if the value of sustainability index is less than 1, and such a production is taxed with an "emergy tax" which is added unit costs of products originating from such a production. A differentiation between sustainable and non-sustainable production is made by using the sustainability index and the following expression (which takes value 0 in the case of sustainable production and the value 1 in the case of non-sustainable production):

$$EESIET = IF(ESI \geq 1, 0, 1), \quad (3)$$

where *ESIET* – effect of environmental sustainability index on emergy tax;

ESI – environmental sustainability index.

Emergy tax per unit of product is calculated as follows:

$$ET = EESIET \cdot NE \cdot ETR, \quad (4)$$

where *ET* – emergy tax per unit of product, EUR/t or EUR/m^3;

NE – non-renewable emergy, seJ/t or sej/m^3;
ETR – emergy tax rate, EUR/seJ.

2.1.2. Causal loop diagram of generic model framework

In Fig. 3, the stock and flow structure is transformed to the causal loop diagram. It illustrates the main feedback structure of the system and helps to capture the causes of dynamics.

In the causal loop diagram presented in Fig. 3, four reinforcing and one balancing loops are represented, - in a second causal loop diagram, presented in Fig. 4 a second balancing loop is illustrated.

Describing the reinforcing loop R1, we start with the land made available for some raw material production. An increase in the raw material made available from that land, allows us to increase the production capacity we establish to produce its derivatives. Thus, if the volume of derivatives increases, then, given the unit value of these derivatives, so does the total value of these derivatives.

We will now assume that the current value of the derivatives produced is relatively high (compared to derivatives from other raw materials). Then so is the relative value of the raw material. In that case, a portion of that increased value, generated from derivatives, will be spent on the purchase of the raw material in question. That will materialize the increased land use for the production of such raw material, indicated by its relatively high unit value.

If we assume that the current value of derivatives produced is relatively low (compared to derivatives of other raw materials), then so is the relative value of the raw material. In that case, *no* portion of that increased value, generated from derivatives, will be spent on the purchase of the raw material in question. That will materialize the decreased of land use for the production of such raw material, indicated by its relatively low unit value, and the land will be reallocated for the production of more valuable raw materials.

Then there is the reinforcing loop R2, again staring with the land made available for some raw material production causing an increase in the total value of the derivatives produced from this raw material. A certain portion of this increased value will be allocated to investments in research and development. Over time, the result will be products and production technology that, potentially,

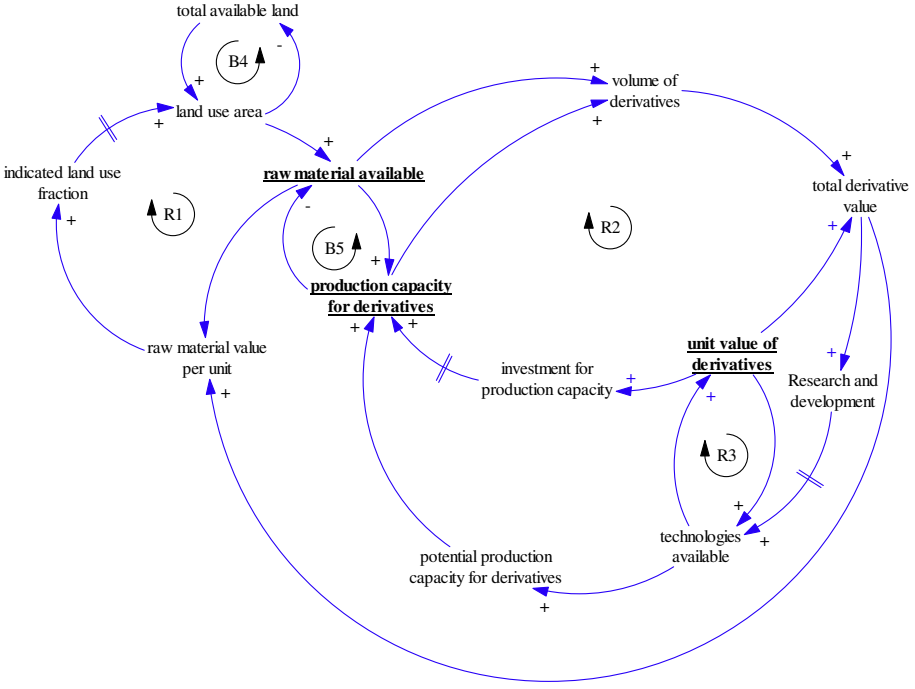

Fig. 3. Causal loop diagram illustrating structure of the model.

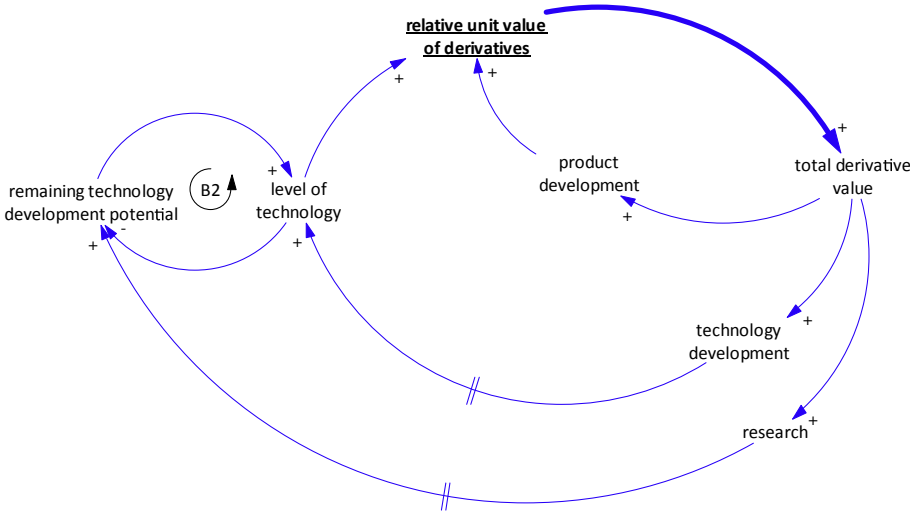

Fig. 4. Causal loop diagram illustrating the main structural components of the model: the three processes that may modify the relative unit value of derivatives.

increases the relative unit value of such derivatives. Below, we will offer a detailed description of research and development and its effects. If the unit value of derivatives increases, then so does the relative unit value of the associated raw material, causing the values earned from the derivative production to be allocated towards additional raw material purchases, - indicating a larger portion of land to be allocated for that production.

Describing the reinforcing loop R3, we start with the production capacity for some derivative production. An increase in that capacity will generate a higher total value of the derivatives produced. A portion of the value generated may be invested in production capacity.

We will now assume that the current value of the derivatives produced is relatively high (compared to derivatives of other raw materials). In that case, a portion of that increased value, generated from derivatives, will be spent on the additional capacity for derivative production.

If we assume that the current value of derivatives produced is relatively low (compared to derivatives of other raw materials), then *no* portion of that increased value, generated from derivatives, will be spent on additional production capacity. A portion of that capacity may remain unutilized and will gradually be discarded and not replaced.

Then, there is the reinforcing loop R4, again staring with the production capacity for some derivative production causing an increase in the total value of those. A certain portion of this increased value will be allocated to investments in research and development. Over time, the result will be products and production technology that, potentially, increases the relative unit value of such derivatives. This causes the values earned from the derivative production to be allocated towards additional production capacity for relatively high value derivatives.

Finally, there is the reinforcing loop R5: An increase in the total value of derivative production, allows for investments in research and developments. The increase in the unit values of derivatives, resulting only after a significant delay, will feed back to increase the total valued of subsequent derivatives produced.

Now we return to the three processes that may modify the relative unit value of derivatives, product development, production technology development and research. In Fig. 1, these processes are all embedded in the bolded relationship between the variables "total derivative value" and "relative unit value of derivatives". They are explicitly represented in Fig. 4 (where the bolded relationship between the variables "relative unit value of derivatives" and "total value of derivatives" represents what we find in Fig. 3). In what follows we will describe each of them, all linking the value produced in the form of derivatives (fueling product and technology development) to the relative unit value of derivatives.

So we start with the total value created by the production of derivatives. A fraction of the value generated may be allocated to product development. In some cases, products developed may be produced with no delay. In other cases there is need for production technology development that eventually will allow for such a production. But if, through product development, the relative unit value of some derivatives may be increased, that will allow for the investment in both additional raw material acquisition and additional production capacity of that derivative, - which will result in an even larger production capacity and thus total value created.

Then, again starting with the total value created by the production of derivatives, a fraction of the value generated may be allocated to production technology development. With some delay, this will cause the level of technology to increase. This will allow us to produce higher value products and/or produce existing products in a smarter way. In any case, that will cause the unit value of derivatives to increase, directing investments towards relatively valuable raw material production (i.e land use) and derivative production capacity so as to produce an even higher total value from derivatives.

The effects of the reinforcing loops associated with technology development, R2 and R4, are dampened by the balancing loop B2: The larger the current level of technology, the more is being utilized of the current technology potential. Thus less of the technology development potential is remaining. Therefore the efficiency of the investment in technology is less, causing the level of technology to grow ever slower.

The only way to compensate for such a technology-saturation, is to raise the technological development potential by research which has the effect of contributing to the reinforcing technology development loops R2 and R4. When a higher production capacity creates a higher derivative value, a fraction of that value may be allocated to research that will lift the technology development potential. And, after an investment in technology development, the current technology level will rise. As describe above, that has the consequence that the production capacity for derivatives may also be allowed to rise.

2.1.3. Added value of product lines of generic model framework

Fig. 5 presents added value chains for product lines created from raw material. When raw material is produced the value is added to it. Raw material can be either sold to final consumer or sold to someone who refines it and adds value to it. The added value depends on the type of derivative. Derivatives 1.1 and 1.2 are traditional products with low added value. By investing in innovation higher added value derivatives (2.2, 3.1 and 3.2) can be produced from the raw material thus providing higher income for economy from biotechonomy.

Fig. 6 illustrates the financial resource flow from added value chains back to economy. Sales of any derivative creates income to product producer. Part of income covers production costs and remuneration for incoming material. The profit stays with the producer of the derivative product.

2.1.4. Assessment of policy instruments

The main question for policy design is: what are the instruments to be used for generation of the maximum added value from the national bio-resources while maintaining sustainable development? The following three factors can be considered as critical for bio-economy development (Fig. 3): bio-resources ("raw material available"), production capacities which allow to process the bio-resources into products ("production capacity for derivatives") and possibility to add value to these resources ("unit value of derivatives").

Several political instruments may be used to increase availability of raw materials, i.e.:

- by supporting production of certain raw materials on the land area available;
- by diverting raw material export to the production of higher added value within country;
- by supporting research, development and education, which in turn should lead to more efficient use of the raw materials.

For development of production capacities, in addition to raw materials, new technologies for production of higher added value products are required ("potential production capacity for derivatives") along with investments for construction of the capacities ("investment for production capacity") (Fig. 3). Several political instruments may be important for development of production capacities:

- support for research, development education to create new technologies for more extensive processing raw materials or adapt technologies which are developed outside of a country;
- support of investment (e.g. investment subsidies) in production capacities.

Unit value of derivatives may increase if demand for raw materials used for production exceeds supply (e.g. in cases of limited availability of the raw materials) or value is added by more knowledge (including design), i.e. "technologies available" (representation of knowledge in causal loop diagram; Fig. 3). Unit value of derivatives may also be increased by more efficient use of resources for production, which is also promoted by "technologies available." Therefore, the main instrument for augmenting unit value of derivatives is support to research, development and education.

3. Verification and validation of model framework

Validation of system dynamics models enables us to understand

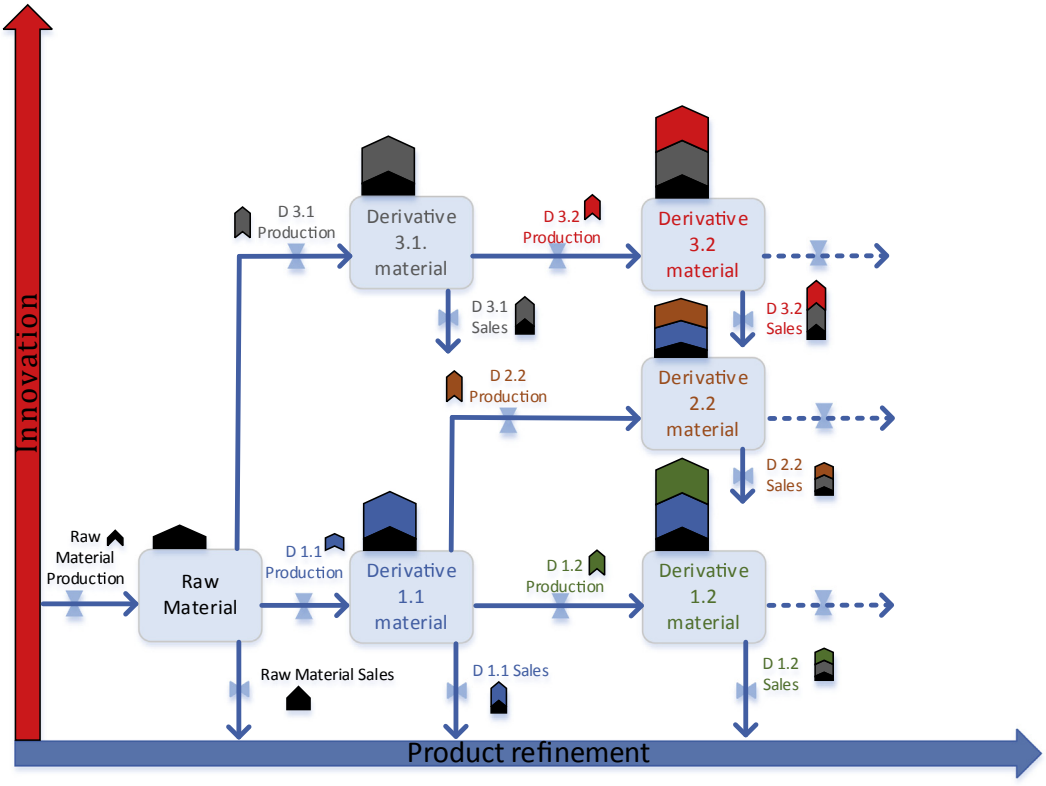

Fig. 5. Added value chains for product lines created from raw material.

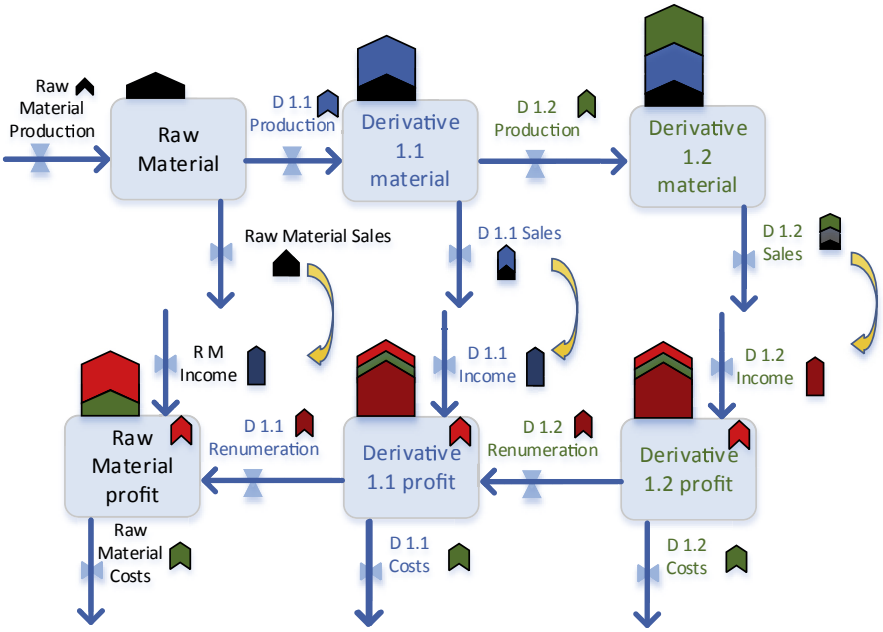

Fig. 6. Financial resource flow from added value chains.

whether the model is acceptable for its intended use (Forrester and Senge, 1980). It also enables us to build confidence in the model based on observations and data from a real system (Barlas, 1996; Sterman, 2000). Barlas (1996) explains why the availability of data is not crucial to create a good system dynamics model. He also states that the validation of system dynamics models has to be carried out rigorously, both for structural and behavioural validation. The verification and validation tests have to be carried out throughout the modelling process. The main goal of verification tests is to eliminate discrepancies between model and the dynamic hypothesis. Verification tests on dynamic hypothesis, unit consistency and simulation time step have been carried out.

Two validation tests have been carried out: structural and behavioural tests, incl. direct structural validity test, parameter confirmation tests, behaviour tests, extreme conditions tests, sensitivity analysis.

4. Application of model framework

The forestry sector and a birch in particular has been selected for the validation and application purposes to demonstrate the framework as a foundation for the assessment of policy instruments aimed at stimulating a profitable and sustainable development of the biotechonomy.

4.1. Background information

Latvia is the fourth afforested country in Europe. Currently, a forest land covers about 52% of the total area and is 3.35 million hectares (LSFS, 2005–2014). Forest area continues to grow and increases because of both the natural and the artificial afforestation of agricultural land. The stock of Latvian forest resources annually increases about three times faster than the forest area. Over the past decade, annual felling rate is about 12 million m^3; of wood (LSFS, 2005–2014). This amount is less than the natural growth rate, so the Latvian forestry can be described as sustainable. Fig. 7 illustrates distribution of tree species in total forest stock in Latvia from which birch has 28% share.

4.2. Forest sub model

Model framework includes forestry sub model where all important parameters are included such as total forest area, share of area and tree species by ownership, share of tree species, stands and age of tree species, felling volumes and forest stock per tree species, felling age of each tree species, felling limits, wood volume in each forest age group, increment rate for each species, forest planting and management costs, changes in forest stock, felling costs, share of leafy biomass, share of branches and bark, bark volume, share of forest assortments per tree species, use of forest assortments per tree species (Krūmiņš, 2014; Daugaviete et al., 2013; Liepiņš et al., 2015; Lazdāns et al., 2009; Silava, 2011; CSBL, 2016; CM, 2015a; CM, 2015b).

4.3. Derivatives from birch wood

Birch wood as raw material is obtained in both public and private forest felling sites. Trees are felled in either clean cut or during forest cleaning. The assortment of birch wood depends on felling type and is divided into four groups: veneer logs, fuel wood, pulpwood and wood residues. Fig. 8 illustrates the products that are already derived from birch in Latvia, as well as those that are likely to be produced.

Currently, majority of birch veneer logs are used for plywood production in Latvia and the rest is exported. 95% of the plywood production is exported and only few percent are used for low and high added value furniture production and building sector in Latvia (LF, 2010; LF, 2014). Waste products from plywood production are used as wood chips for energy production. Felled fuel wood is dried and sold as fuel either as wood logs, wood chips or wood pellets. Forest residues such as branches and stumps are chipped thus producing wood chips for energy production (MEKA, 2015).

Selection of higher added value products for modelling is based on the research carried out by Latvian Institute of Wood Chemistry (LSIWC (2009); LSIWC (2013)) and forecasted developments by (Hetemaki, 2014). From birch bark, which is a veneer production waste product, can be made betulin and lupeol (Pāže, 2015; Fridén

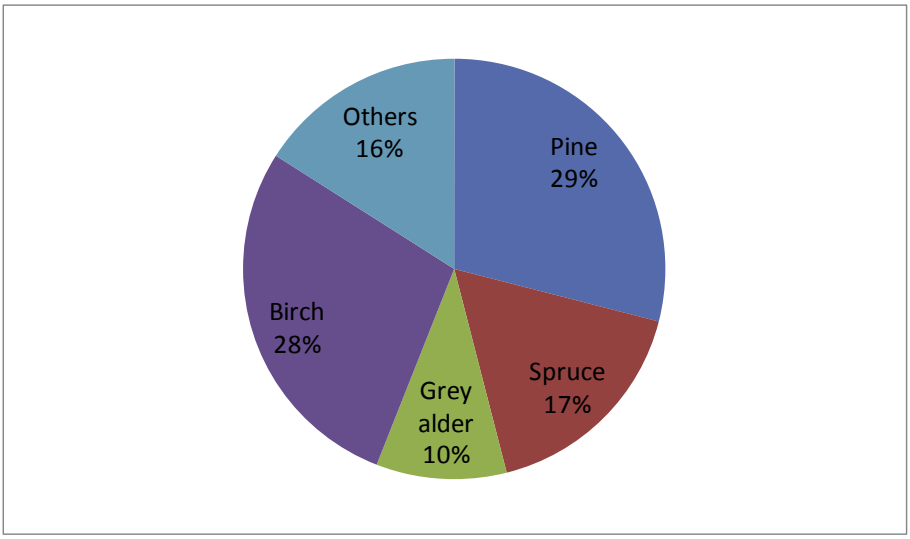

Fig. 7. Tree species distribution in total forest stock in Latvia.

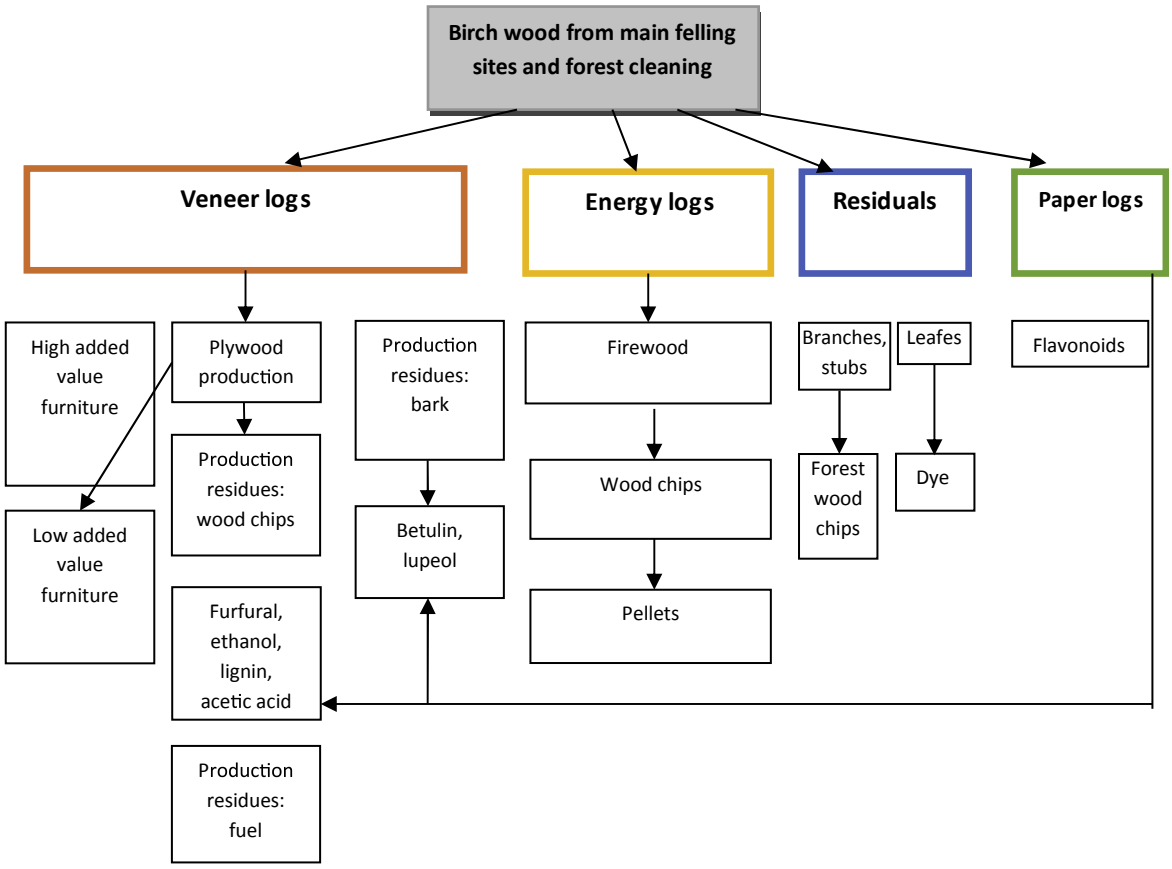

Fig. 8. Birch-derived products used in model.

et al., 2015; Ekman et al., 2013). Extracted bark is used as a fuel. Other plywood production residues can be chipped and used for simultaneous furfural, ethanol, acetic acid and lignin production (Kautto et al., 2014). Extraction residue from this process can be used as fuel. The leaves can be used to extract dyes and flavonoids (Leitão et al., 2013). These derivatives are used just to illustrate the application of modelling framework. In the following studies, the model can be supplemented with many other birch-derived products such as nanocelullose, multifunction carbon materials based on lignocellulose, insulation materials, coating materials, composite materials, carbon sorbents, superconductors, multi-purpose organic and inorganic hybrid materials and poly-complexes, levoglicosane, polyurethane foam from lignin, coatings of cellulose and hemicellulose, building materials, etc.

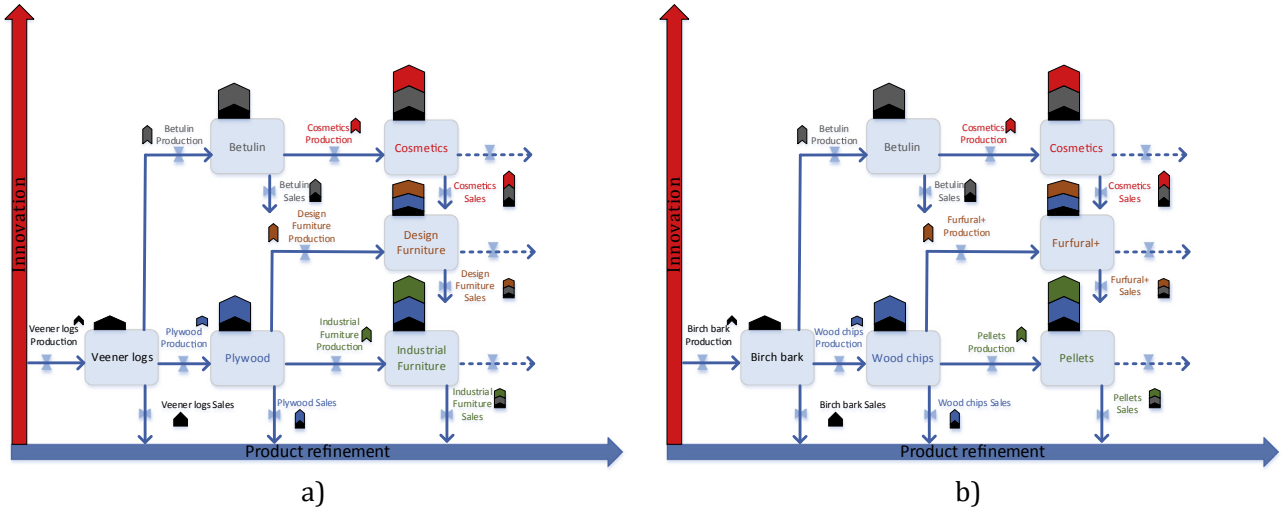

Fig. 9. Added value chains for product lines created from (a) birch veneer logs and (b) birch bark.

Fig. 9 shows application example of added value chains for product lines created from birch veneer logs (a) and birch bark (b) material. Veneer logs currently are used to produce plywood and low added value or mass production furniture as well as some higher added value furniture. If betulin is produced from birch bark instead of using it as energy fuel, and used in pharmaceutical or cosmetology production much higher value can be added to birch veneer logs.

5. Results

5.1. Added value of derivatives

Fig. 10 illustrates changes of value added share of different currently produced birch wood derived products until 2030 with respect to the total added value of birch wood derived products. The electricity tariff and heat tariff increase is assumed to be 1.5% per year, labour cost growth of 3% per year (with the exception of birch plywood production, which is in accordance with the manufacturer's publicly provided data is scheduled for 7% per year) and the price of wood raw material and finished product price increases of 2% per year. As the result the largest share of added value is provided by birch plywood production, followed by a birch felling sector and fuel wood (firewood, industrial wood chips, wood chips and pellets) production, but the smallest share belongs to furniture production.

Fig. 11 shows changes of added value share of birch derived currently produced and new products (betulin, incl. lupeol; furfural, incl. ethanol, acetic acid, lignin and electricity production, and flavonoids) compared to the total added value of birch derived products by 2030. The electricity tariff and heat tariff increase is assumed to be 1.5% per year, labour cost growth of 3% per year (with

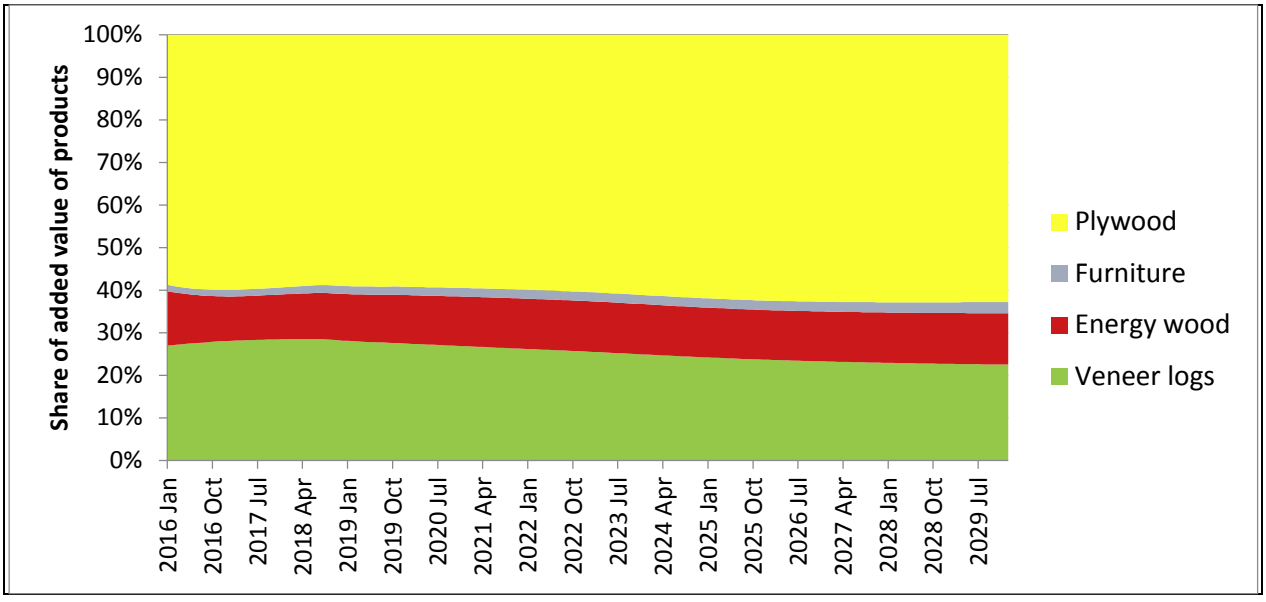

Fig. 10. Share of currently produced birch wood derived products added value from the total added value from birch wood derived products.

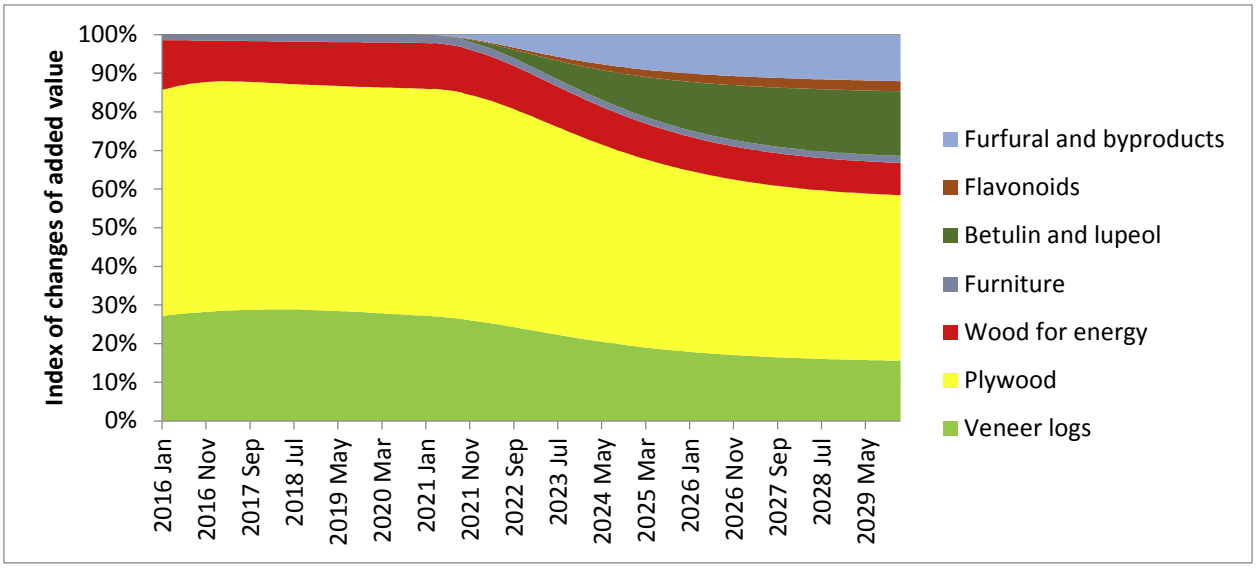

Fig. 11. Share of currently produced and new birch wood derived products added value from the total added value from birch wood derived products.

the exception of birch plywood production, which is in accordance with the manufacturer's publicly provided data is scheduled for 7% per year) and the price of wood raw material and finished product price increases of 2% per year. Initial shares are the same as in Fig. 10. New products enter the market in 2020 and their added value is increasing every year, reducing the share of existing products down to 70% and increasing the share of new products up to 30% in 2030.

Fig. 12 shows the value added index of new and existing birch wood derived products. As a reference year for value added index calculation is used 2016. The same assumption as for Figs. 10 and 11 are used. If only production of currently produced products would continue, then in 2030 the total added value of the product would be 1.7 times higher than in 2016. However, if additionally to the existing products new products are produced, the total added value would increase 2.45 times compared to 2016 and give a significant contribution to the national economy.

If the electricity tariff and heat tariff increase rate was higher (3% per year), labour cost growth was 7% per year, the increase rate of price of wood raw material was 4% per year and finished product price increases of 2% per year, the total added value of the existing products would be 1.6 times higher in 2030 than in 2016, but by adding new products are produced, the total added value index would increase 2.3 times compared to 2016.

5.2. Added value chain

An example of the added value chain for birch veneer logs derived products. At the beginning of modelling (2016) the birch veneer logs are used for production of birch plywood. Of these, only 0.1% are used for production of high-value-added, or design furniture. The waste products of plywood production are wood chips and birch bark and they are used as firewood. The new products include use of wood chips for simultaneous use of furfural, ethanol, lignin, acetic acid and the production of electricity, as well as birch bark use of simultaneous production of betulin and lupeol. In

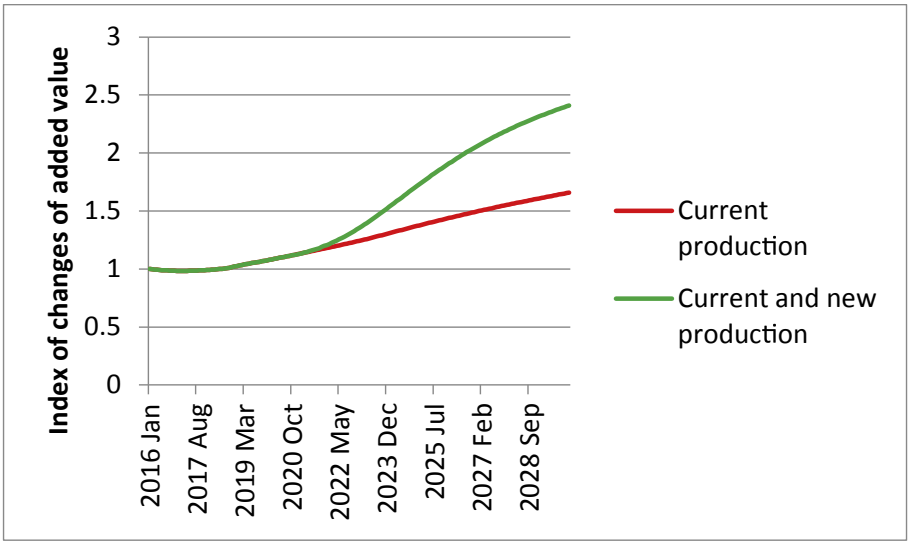

Fig. 12. The value added index of new and existing birch wood derived products.

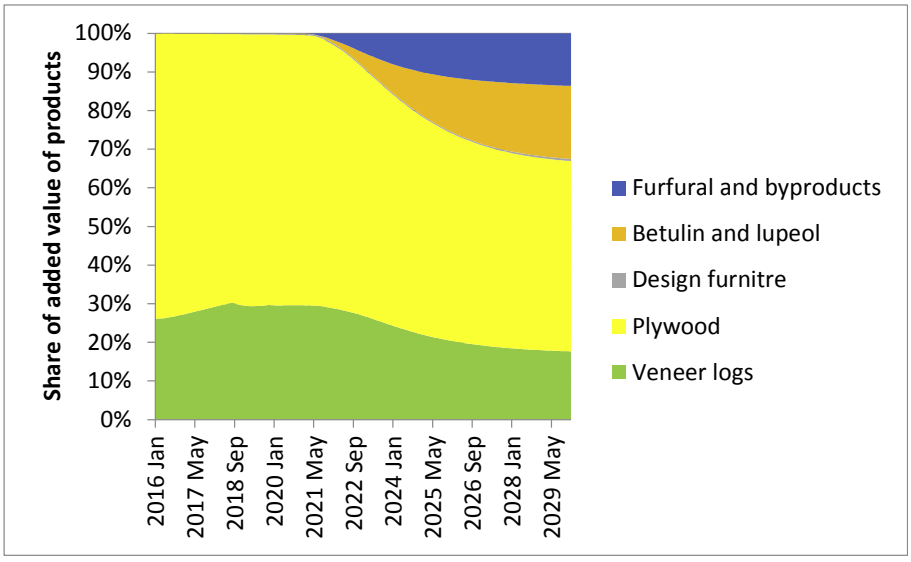

Fig. 13. Shares of added value of different birch veneer logs derived products from total added value to birch veneer logs.

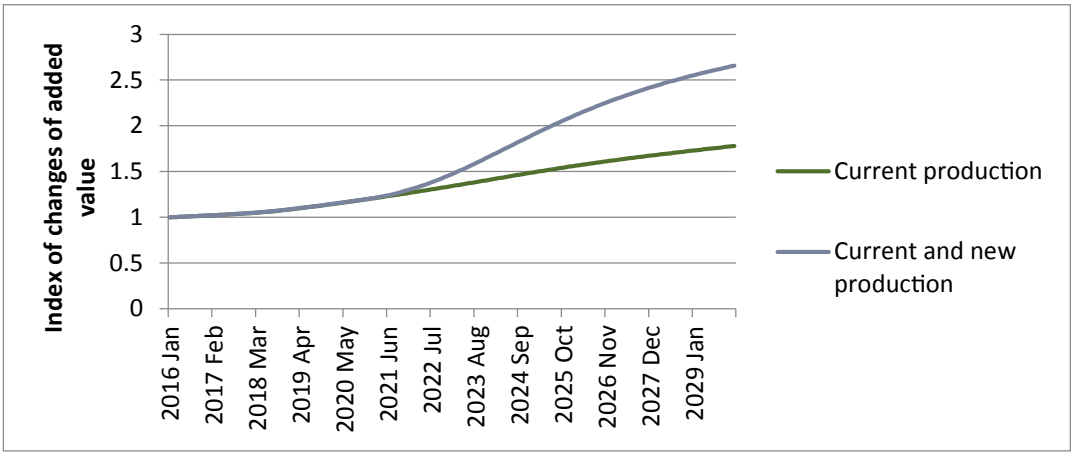

Fig. 14. The value added index of new and existing birch veneer logs derived products.

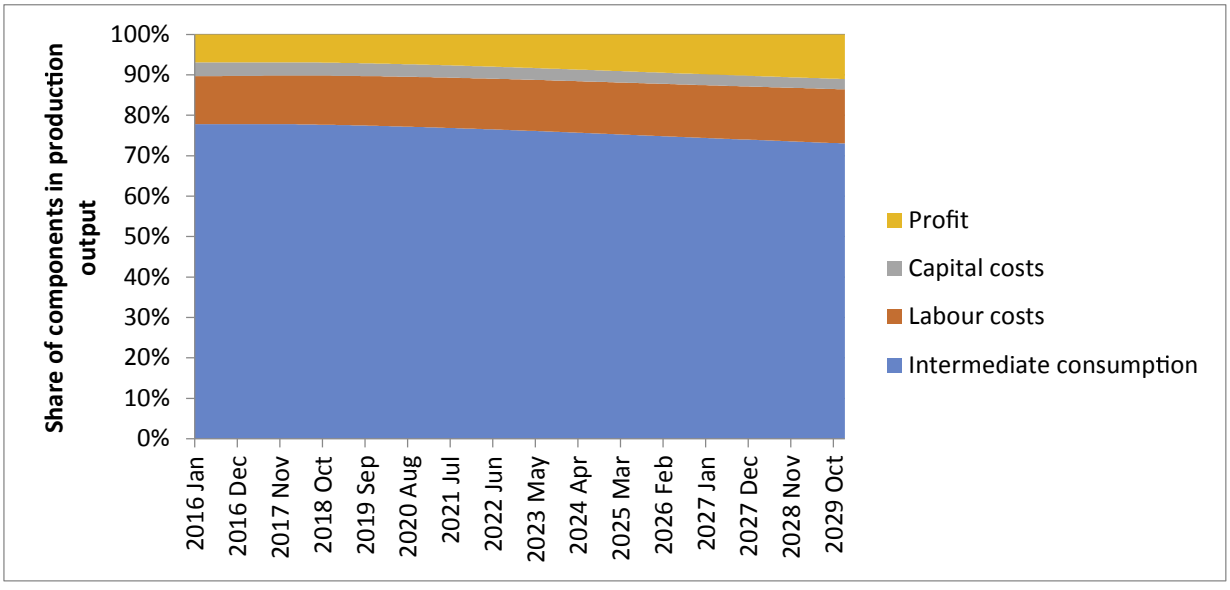

Fig. 15. The breakdown of output value of currently manufactured products with low added value.

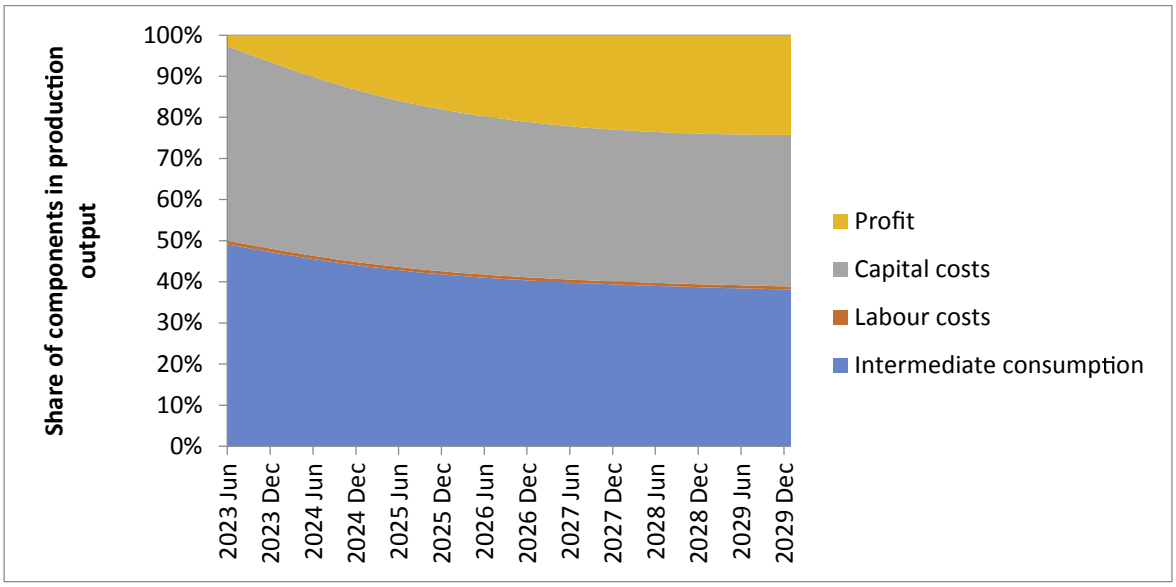

Fig. 16. The breakdown of output value of new products with medium added value and high capital costs.

addition, the growth rate of high value-added furniture production is increased. The model assumes that new products are starting to be produced from 2020. Fig. 13 shows shares of added value of different birch veneer logs derived products. At the beginning of the simulation the greatest share belongs to plywood production, but by the time it is shrinking because of the appearance of new products with higher added value.

Fig. 14 shows the added value index for the new and existing products that are manufactured from birch veneer logs. Year 2016 is used as a reference point, and the added value index is calculated against this reference point. The same assumption as for Figs. 10 and 11 are used. If only production of currently produced products would continue, then in 2030 the total added value of the product would be 1.8 times higher than in 2016. However, if additionally to the existing products new products are produced, the total added value would increase 2.7 times compared to 2016.

5.3. Breakdown of the output value for different derivatives

The structure of the model allows taking a closer look at the output value breakdown of each derived product. The value of each product is divided into intermediate consumption and value added, incl. the cost of labour, cost of capital and profit. These parameters and their share are time-varying. The dynamics of changes vary across different product types, e.g. products with low added value, products with an average value-added and large capital investment, and products with high added value.

Fig. 15 illustrates the breakdown of output value of currently manufactured products with low added value. In this case the largest the share belongs to intermediate consumption, followed by labour costs, profit and capital costs.

If a new product is produced with a medium added value and high capital costs, the highest share in output value is taken by intermediate consumption and capital costs, followed by labour

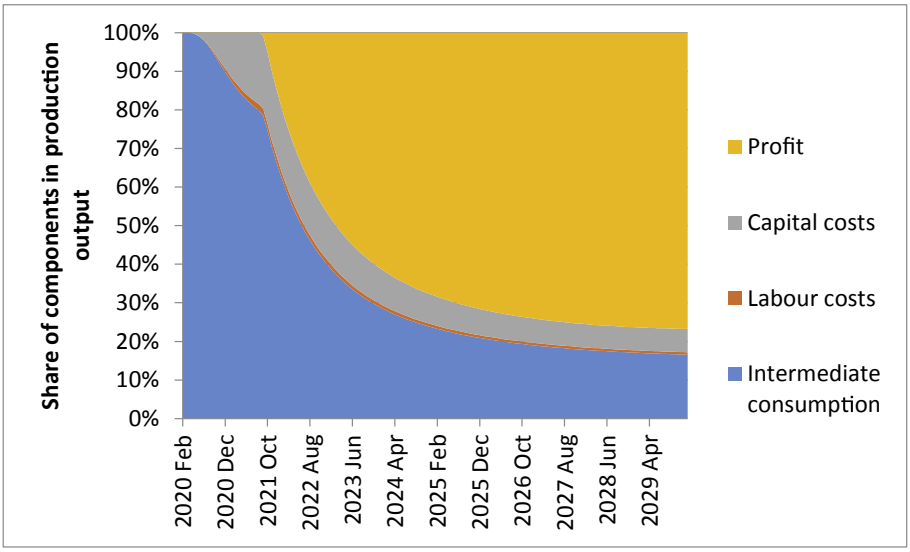

Fig. 17. The breakdown of output value of new products with high added value.

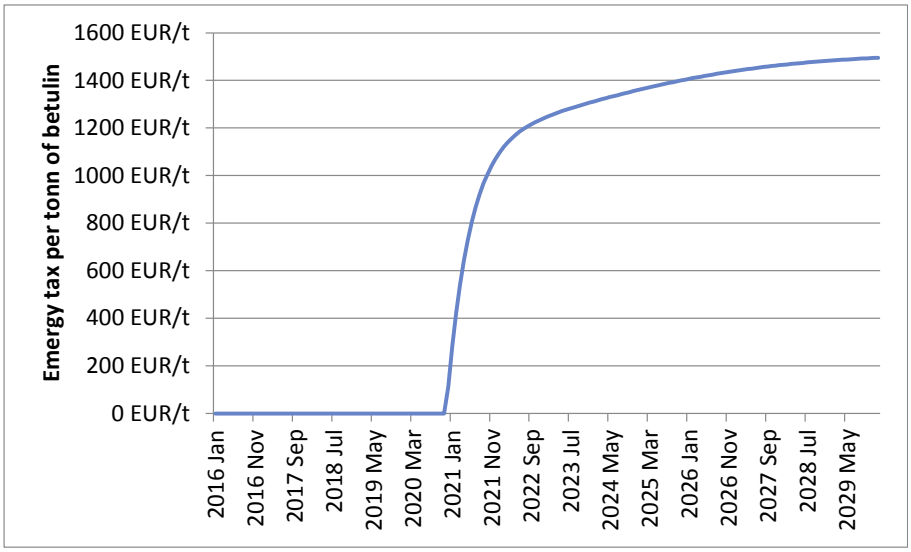

Fig. 18. Changes in emergy tax for production of one ton of betulin.

costs and profit. Initially, profit represents a very small share, but when the production volume grows, profit increases, but it does not reach neither the share of capital costs, nor the share of intermediate consumption (see Fig. 16).

Fig. 17 presents output value breakdown of an example of a new product with high added value. Starting production, intermediate consumption accounts for most of the production value, followed by the capital costs and labour costs. During the first years there is no profit, but it is beginning to take shape after a few years of operation and is growing rapidly, and reaching the highest share.

5.4. Emergy tax

If emergy tax rate is assumed to be €100/seJ, some of the birch wood derived products should have include it in the output value, for example, birch plywood, furfural and its by-products, betulin and lupeol, as well as flavonoids and firewood. For some of the products would have serious impact on the price, such as birch plywood production, while for other products the effect is very small. Fig. 18 gives an example of dynamics of the emergy tax for betulin and lupeol production.

6. Discussions and conclusions

In this study we have created and verified the structure of a generic framework model for a biotechonomic sectors; their land use, production and consumption of raw material, research and development, investments in and utilization of production capacities, their utilization of labour, finances, and sustainability. The model resulting from the research considers accumulation processes, causing delays in their response to incentives; feedback processes, causing a reinforcement or dampening of such a response; nonlinearity, causing an interaction between the response produced by various sector components and across sectors; and uncertainty.

Application to the forestry sector and birch-derived products in particular shows that the model framework provides not only general information about development of the system over time but also gives insights into the structural details. This in turn allows explaining internal dynamics of the system. While added value of derivatives and the value added index of new and existing products illustrate changes of added value over the time, breakdown of the output value for different derivatives provides understanding of structural differences between different products' production processes. Model also allows simulation of employment based on type of competencies, requirements for education system, energy consumption based on technological development, investments required, impact of research and development on yields of raw material and other micro, meso and macro level biotechonomy indicators. The emergy indicators allows to take into account environmental impact of any activity.

The following three factors are considered as critical for bioeconomy development: bio-resources, production capacities which allow to process the bio-resources into products and possibility to add value to these resources. Policy tools built into the model framework are tackling each of these factors.

The model framework is like Lego bricks. They can be built in different combinations hence it is useful tool for application in any of three levels: micro, meso and macro. It can either be applied for analysis at micro level of one enterprise/consumer, for example plywood production. It also can be applied for meso level analysis of eco-industrial systems, industrial symbiosis districts and networks, for example symbiosis of plywood producers, betulin producers, pellets producers and cosmetics producers. The generic framework can be used in macro level analysis of city, province, region, nation, for example, development of national bioeconomy strategy, national development plans or urban symbiosis.

The further development of the model framework will include macro economics sub models such as demographics, national education system, health system.

In this study we have created and verified the structure of a generic framework model for a biotechonomic sectors and applied it to the forestry birch-derived products.

Acknowledgment

The authors would like to express appreciation for the support of EEA grant project "Development of bioeconomical model for sustainable use of biological resources in order to reduce climate changes and improve adaptation capacity (BIO-CLIMATE)".

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